III.C.3 Low-Cost Soft-Switched DC/DC Converter for Solid Oxide Fuel Cells

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Subcontractor: EPRI-PEAC Corp., Knoxville, Tennessee

Objectives

- Develop a low-cost DC/DC converter for low- to high-voltage power conversion as the standard interface between the solid oxide fuel cell (SOFC) source and the load-side DC/AC inverter.
- Achieve 97% DC/DC conversion efficiency for the Solid State Energy Conversion Alliance (SECA) 5-kW solid oxide fuel cells.
- Advance high-power DC/DC converter technology with high-efficiency soft switching and high-performance digital-controlled techniques.

Approach

- Develop an interleaved multiphase isolated DC/DC converter (V6 converter) that reduces the ripple going back to the fuel cell and the ripple appearing at the output.
- Develop a phase-shift modulated soft-switching technique to eliminate switching losses of the DC/DC converter.
- Develop a dynamic fuel cell model for strategizing the fuel cell energy management and the DC/DC converter control.
- Design a high-frequency planar transformer to reduce the size of the complete system.
- Design an intelligent digital controller for high-performance SOFC power conversions.
- Test the converter with a calorimeter to characterize the converter efficiency.

Accomplishments

- A novel multiphase isolated DC/DC converter has been developed for low-voltage input and high-voltage output, especially for SECA SOFC applications. A prototype 5-kW V6 converter has been designed, fabricated and tested to demonstrate 97% efficiency over a wide load range.
- An intelligent current sensor-less control technique has been developed for high-performance DC/DC converters.
- A dynamic fuel cell model has been developed and proven with a commercially available proton exchange membrane (PEM) fuel cell for converter simulation and for strategizing controller design and energy management. The model will be modified for solid oxide fuel cells with minor changes of the time constants.
- Two calorimeters have been built and characterized for DC/DC converter efficiency measurement.

Future Directions

- Continue testing the DC/DC converter to full power with the calorimeter.
- Address fuel cell current ripple reduction issue in the converter design.
- Design the package for the V6 DC/DC converter that incorporates a DC/AC inverter.
- Design the solid oxide fuel cell interface and communication.
- Test DC/DC converter electromagnetic interference (EMI) performance at EPRI-PEAC Corp.
- Test DC/DC converter with the solid oxide fuel cell.

Introduction

While the efficiency of the SOFC stack is crucial to the entire power plant efficiency, the inefficient power electronics can eat up all the gains in SOFC stack development. As shown in Figure 1, the SOFC-based power plant consists of multiple-stage power conversions including a DC/DC converter and a DC/AC inverter to obtain utility AC voltage. It is nontrivial to achieve high efficiency for multiple-stage power conversions. The most important power conversion stage in this SOFC power plant is the DC/DC converter, which takes low-voltage SOFC output DC and converts it to high-voltage DC through a 3-stage power conversion. Currently, the commercial off-the-shelf DC/DC converter is normally less than 90% efficient and is not available at 5-kW or higher power level.

Efficiency translates not only to fuel savings but also to cost reduction because a smaller membrane electrode assembly (MEA) can be used for the same power output. Thus, the primary focus of this project is to develop a low-cost DC/DC converter that achieves 97% efficiency at 5 kW for SECA SOFC power plants. Given that the SECA SOFC voltage output is as low as 20 V and the silicon bandgap is 0.7 V, any single junction voltage drop in silicon devices would drop the efficiency below 96.5%.

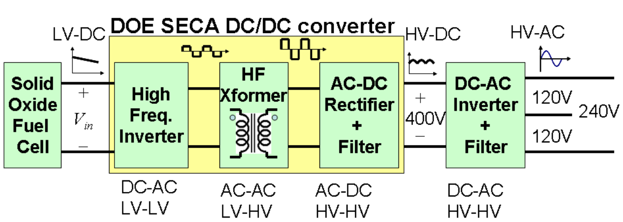

Figure 1. Block Diagram of a SOFC-Based Power Plant Showing a DC/DC Converter as the Most Important Power Conversion Stage

Thus, the design of the highly efficient DC/DC converter is very challenging and requires innovative ideas and substantial engineering effort.

Approach

A novel interleaved multiphase isolated DC/DC converter has been proposed and developed for cost reduction and efficiency improvement. This newly developed converter has been named as "V6 converter" because it resembles a V6 engine for high-horsepower vehicles. With 6-phase legs interleaved operation, the V6 converter significantly reduces the ripple going back to the fuel cell and the ripple appearing at the output. The structure of the converter also allows phase-shift modulation to eliminate the switching loss. An optimized transformer turns ratio has been designed to avoid device body diode conducting that generally consumes more than 7% of the total conduction loss.

In order to design a controller that matches the fuel cell dynamic response, a dynamic fuel cell model has been developed for the entire fuel cell power plant simulation to verify the fuel cell energy management and the DC/DC converter control strategy. An intelligent digital controller is being developed for high-performance power conversions to ensure system stability under any transient and dynamic conditions.

Results

Figure 2 shows the schematic circuit diagram and the 5-kW prototype of the proposed 6-phase leg (V6) isolated DC/DC converter. The schematic circuit diagram only shows one DC output; however, the actual prototype has two DC outputs that allow interfacing to a dual-output DC/AC inverter.

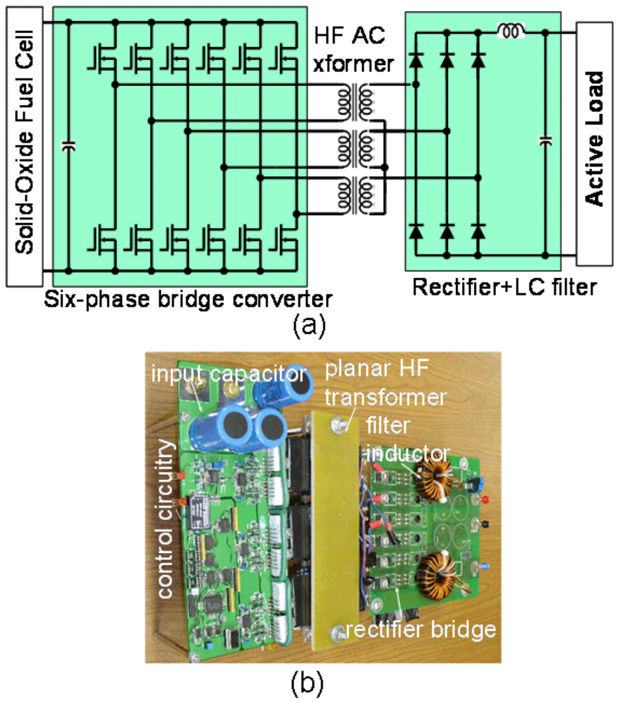

Figure 2. Circuit Diagram and Photograph of the Proposed V6 DC/DC Converter: (a) Schematic Circuit Diagram; (b) Photograph of the 5-kW Converter Prototype

For the 6-leg DC/DC converter, every two-phase leg pair forms a full-bridge converter that can be operated at zero-voltage switching condition with phase-shift-modulation control. Three full-bridge converters are phase-shifted 120° with transformer current interleaving each other to cancel the high-frequency ripple at both input and output; thus, the size of the input filter capacitor and output filter inductor can be largely reduced. These passive components reduce the size and cost by 6 times compared to the single-phase leg converter. The multiphase converter also avoids device paralleling associated parasitic losses and reliability degradation problems. The novel multiphase isolated V6 converter has been developed for low-voltage input and high-voltage output, especially for SECA solid oxide fuel cell applications. A prototype 5-kW converter has been designed, fabricated and tested to demonstrate 97% efficiency over a wide load range.

The DC/DC controller is implemented with a proprietary digital phase-shift controller. It produces very precise phase-shift angles between three full-

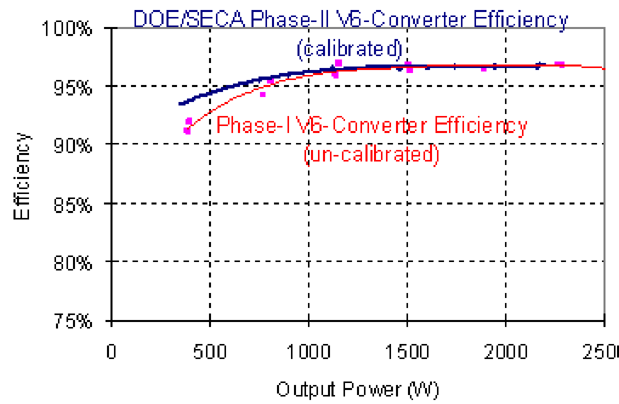

Figure 3. Measured Input and Output Voltage Waveforms for (a) Conventional Full Bridge Converter and (b) the Proposed V6 Converter

bridge converters to avoid the unbalanced output-induced circulating current. The transformer output is tied in Y-connection to double the output with a lower turns ratio, thus avoiding significant leakage inductance and its associated losses. The turns ratio is also optimized to avoid circulation current associated losses. The phase-shift modulation allows the devices turning on at zero voltage to eliminate the switching loss. Thus, the only major converter losses are in device conduction, and the system efficiency can be manipulated with proper selection of low-voltage-drop semiconductor devices.

Figure 3 compares measurement results of input and output voltage and current waveforms for the conventional full-bridge DC/DC converter and the proposed V6 converter. The full-bridge converter not only shows poor efficiency of about 87% at the 1-kW test condition, but also presents significant electromagnetic interference noise on the output voltage. The proposed V6 converter, however, shows very clean voltage and current waveforms and a high efficiency of 97% at the same power level.

The efficiency measurement has been very inconsistent during Phase I testing. The numbers were all over the place and occasionally exceeded 100%. Since the only trustable efficiency measurement is from thermal measurement, we built a calorimeter and calibrated all the sensors and data acquisition units in the Phase II effort. The calibration for thermal measurement is very time consuming, typically taking 8 hours to reach thermal

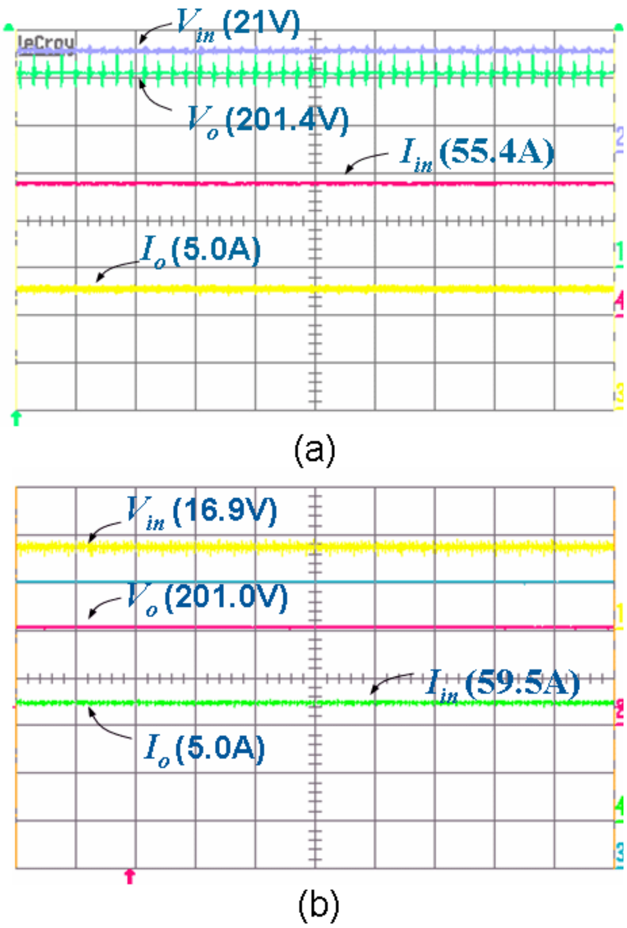

Figure 4. Efficiency Measurement Results of the V6 DC/DC Converter Showing Both Un-calibrated Phase-I and Calibrated Phase-II Results

equilibrium, but is the only way to have high confident level. Figure 4 shows the efficiency measurement results of the V6 DC/DC converter with both un-calibrated Phase-I and calibrated Phase-II results. The calibrated results were obtained from the average of 10 data acquisition points, while the un-calibrated results were obtained from human eye monitoring. The results agreed reasonably well with each other at most power levels. However, the Phase-II converter has better efficiencies at lower powers and is expected to show better results at higher power level as well. The reason we have not pushed to higher power is because the sensor has been calibrated only at 5 A for the two output current measurements, and the maximum output power can be measured at about 2 kW.

We also developed a dynamic fuel cell model and proved it with a commercially available PEM fuel cell for converter simulation and for strategizing controller design and energy management. The model will be modified for solid oxide fuel cells with minor changes of the time constant. To date, the converter control system design has been based on the PEM fuel cell dynamics and has been proven to be stable under load transient conditions. Once the SOFC dynamic model is known, we will modify the controller time constant accordingly to ensure stability.

Conclusions

The proposed V6 DC/DC converter shows superior performance and achieves the SECA efficiency goal in a wide power range. The major effort and achievements can be summarized as follows.

- Successful development of highly efficient DC/DC converter.
- Successful development of low-loss low-profile high-frequency transformer.
- Successful development of highly précised digital phase-shift modulation controller for the V6 converter.
- Calibration of loss measurement and calorimeters.
- Modeling of fuel cell dynamics for DC/DC controller and fuel cell energy management system designs.

The proposed V6 converter has been characterized with the following distinct features:

- High efficiency – 97% over a wide load range
- Low input current ripple – 6X reduction over conventional technologies
- Low output current ripple – 6X reduction over conventional technologies
- Small input filter capacitor – 6X reduction over conventional technologies
- Small output filter inductor – 6X reduction over conventional technologies
- Low cost – significant reduction on passive components (6X) and heat sink size

- Low EMI – soft switching over a wide load range and interleaving to cancel ripples
- High stability – controller design based on the fuel cell and converter dynamic models

FY 2004 Publications/Presentations

1. Changrong Liu, Amy Johnson, and Jih-Sheng Lai, "A Novel Three-Phase High-Power Soft Switched DC/DC Converter for Low Voltage Fuel Cell Applications," in Proc. of IEEE Applied Power Electronics Conference, Anaheim, CA, February 2004, pp. 1365 – 1371.

2. Jih-Sheng (Jason) Lai, "A High-Efficiency Low-Cost DC-DC Converter for SOFC Performance and Control of V6 Converter," Presentation at SECA Core Technology Program Review Meeting, May 13, 2004.

3. Jih-Sheng (Jason) Lai, "Fuel Cell Power Conditioning," Keynote Speech at ASME International Conference on Fuel Cell Science, Engineering and Technology, June 14-16, 2004.

4. Changrong Liu, Amy Johnson, and Jih-Sheng Lai, "Modeling and Control of a Novel Six-Leg Three-Phase High-Power Converter for Low-Voltage Fuel Cell Fuel Cell Applications," in Proc. of IEEE Power Electronics Specialists Conference, Aachen, Germany, June 2004, pp. 4715 – 4721.

Special Recognitions & Awards/Patents Issued

A Patent Disclosure is in the process of filing through Whitham, Curtis & Christofferson, RC Intellectual Property Law for the Multiphase Soft-Switched DC-to-DC Converter.